

technical field of the invention

10 Technical background and related art

20 Although current optical fibres exhibit extremely
low losses, optical repeaters are needed if transmission
is carried out over long-haul transmission lines. Such
optical repeaters typically comprise fibre amplifiers for
amplifying the optical signal propagated by the fibre.
25 The amplification in the amplifiers is normally slightly
different for different wavelengths, i.e. for different
channels within the WDM signal. Moreover, different
wavelengths may experience different losses along the
optical network. Therefore, the relation between the
30 power levels of the individual channels is not preserved
throughout the network.

It is often desirable to maintain a constant power distribution between the channels, or to maintain a

5 introduce "gain equalisation", also known as channel
balancing. A small variation between the channel powers
at the transmitter can cause large variation between the
channel powers at the other end. In general, the power
levels of the different channels will change
0 unpredictably as the signal propagates through the
optical network. To overcome this problem, different
approaches have been proposed.

To improve the channel balancing, it was proposed to equalise the channels at every amplifier stage. This could be done by demultiplexing the channels after each amplifier stage, then attenuating each channel separately, and subsequently multiplexing the channels back together for further transmission through the network. However, this approach required a very complex structure of hardware, and added tolerance penalties in the demultiplexing/multiplexing stages. For these reasons, this approach was not feasible for commercial use.

Alternatively, a multi-channel filter could be used. One example of such filter is an acousto-optic tuneable filter (AOTF). An AOTF uses an RF signal to attenuate each channel independently of the others. However, the
5 AOTF requires high amounts of driving power to balance more than a few (2-4) channels, and there is an increased tendency to cross-talk between the channels due to the acousto-optic filtering. Consequently, the use of an AOTF is not feasible when trying to equalise a large number of
10 channels in a DWDM signal.

Another method is to use carefully designed passband filters to equalise the channels. Since this method is not tuneable, it is of minor importance in high-performance optical networks. Furthermore, fixed filters
15 are believed to cause difficulties when used in connection with dynamic routing of channels, in which case it is not known in advance which way a certain channel will travel through the network.

A recent effort towards channel balancing is
20 disclosed in US-A-6 134 034. In that case, feedback from a receiver to a transmitter controls the power levels of individual channels before multiplexing the channels together. In essence, this is just pre-equalisation. As mentioned above, serious problems are connected with such
25 an approach. Firstly, the method is only feasible for point-to-point connections. If the network is constituted by a mesh, in which the channels can take any route, the principle does not apply. Secondly, and as mentioned above, pre-equalisation is sometimes not enough. This is
30 particularly obvious when it is not known at the transmitter which route each channel will take through the network.

Consequently, there is a need for new methods and apparatus for channel balancing that can allow any
35 routing through the network, that can be located at any point in the network, and that dynamically equalise the

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The present invention is based on a deep insight into resonantly enhanced channel separation in the optical domain, and into the characteristics of Bragg gratings and how such grating work when provided in connection with a waveguiding structure. When a resonator is operatively connected to a waveguiding structure such as an optical fibre, a set of wavelength intervals will start to resonate in said resonator. Consequently, a high power level will build up inside the resonator, effectively filtering out the resonant wavelength(s). If attenuation is applied to a carefully selected portion of a waveguiding structure, comprising resonantly enhanced channel separation, attenuation will be provided predominantly to desired channels.

Channel balancing includes adjustment of the power level of one wavelength channel to a desired value. Thus, each channel within the WDM optical signal has an associated desired value. The desired value could be equal for all channels, in which case the channel balancing causes the power level of all channels to be equal. In other cases, the desired value could be set according to some predefined profile. Such profile, for example, could compensate for known losses in a transmission system before sending the optical signal (pre-equalisation of channels). The desired value could also be such that each channel exhibits the same signal-to-noise ratio, i.e. channels for which more noise is expected in the system are given a higher power level than those for which less noise is expected. Noise is introduced by, for example, amplifiers in the transmission system (such as amplified spontaneous emission in fibre amplifiers). Generally, the desired values could be set according to any input, including user input by means of a control console, the invention

not being limited to any particular method for establishing the desired values.

In one aspect, the present invention provides a method for channel balancing of a WDM optical signal, by which method single wavelength channels can be attenuated separately. Channel separation according to the invention is achieved by providing a resonator that is resonant to at least one wavelength channel within said optical signal. The resonator establishes a region where the resonant channel has a substantially increased power density with respect to non-resonant wavelength channels. According to the invention, attenuation is provided in said region of increased power density. Attenuation is thus predominantly applied to the resonant channel, although the attenuation means *per se* might be non-discriminating in terms of wavelength.

In another aspect, the present invention provides an arrangement for channel balancing of a WDM optical signal. The arrangement comprises a spectrum analyser for analysing the power spectrum of the optical signal, and an attenuator for attenuating single wavelength channels within said optical signal. The arrangement further comprises a resonator that is resonant to at least one specific wavelength channel within the optical signal, and provides a selection region where a selected signal has a substantially increased power density in relation to channels out of resonance. Furthermore, the attenuator is arranged to attenuate said optical signal by acting upon or by adjusting the properties of the selection region. Thus, by providing a region where one channel within the optical signal is predominant, channel specific attenuation can be attained by using attenuation means that are essentially non-discriminating in terms of wavelength.

In another aspect, the present invention provides dynamic optical filters, or couplers, that can be arranged in cascade. The present invention provides

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Thus, according to one embodiment of the present invention, attenuation of one channel is achieved by

dividing the power of said channel in two portions, and then adjusting the phase of one of said portions so that when the two portions are brought back together, destructive interference occurs in the propagation direction of the optical signal. More particularly, an arrangement for attenuation by destructive interference comprises a waveguiding structure, preferably an optical fibre, into which the wavelength division multiplexed optical signal is directed. In said fibre, there is provided a deflector arranged to deflect light into an external resonator, said deflector preferably comprising a blazed, or tilted, phase grating. The external resonator can be tuneable in order to allow tuning of the wavelength to which said resonator is resonant. The deflector is weak, in that it only deflects a small fraction of light impinging thereupon. However, a strong field will quickly build up inside the resonator at the wavelength interval (or intervals) to which the resonator is resonant and thereby establish a selection region in which the power density of the resonant wavelength is considerably higher than of other wavelengths. Thus, at equilibrium, higher power will be reflected back and forth between the mirrors inside the external resonator, and the power deflected into the resonator from the fibre will be equal to the power deflected out from the resonator back into the optical fibre. By adjusting the phase of the light inside the external resonator, destructive interference between light from the resonator and light remaining in the fibre can be obtained in a selected propagation direction. Hence, by tuning the external resonator, it is possible to prevent light of the resonant wavelength from propagating in a selected direction in the fibre. Likewise, it is possible to achieve fractional destructive interference, and thereby prevent only a fraction of the resonant wavelength from propagating in a selected direction. In this way, tuneable attenuation of the channel power is attained.

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The features of this embodiment will be fully understood when the detailed description below is read.

In another embodiment, similar to the one described above, the external resonator is constantly tuned (or
5 fixed) to provide constructive interference. According to this embodiment, attenuation is achieved by introducing a loss in the external resonator. Consequently, when the two portions of the channel are brought back together, the resulting power is lower than the power before
10 dividing the channel. Typically, it is possible to achieve up to about 50 percent attenuation with this embodiment.

According to yet another embodiment of the present invention, the external resonator encloses two optical
15 fibres. The selection region provided by said resonator is then responsible for the coupling of the resonant wavelength between said two fibres. The coupling factor between the two fibres can be tuned by adjusting the properties of the external resonator, and thereby provide
20 tuneable attenuation of the selected channel at the coupling between the two fibres. Alternatively, a variable loss can be introduced into the external resonator.

Other embodiments of the present invention rely on
25 an internal resonator, rather than the external resonator described above. The internal resonator is preferably co-linear with the propagation direction of the waveguiding structure. Such internal resonator is provided by arranging at least one Bragg grating in the waveguiding
30 structure. Preferably, said grating is a chirped Bragg grating being resonant to different wavelengths at different positions along the same. A controllable amount of power can easily be removed from one channel of the wavelength division multiplexed optical signal at the
35 position of the corresponding resonance. Wavelength selective coupling assisted by a chirped Bragg grating is described in the co-pending application "Optical

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According to the present invention, the internal resonance provides a selection region in which attenuation can be obtained by introducing, for example, a loss. The loss can be of simple nature, for example a micro-bend of the fibre, said micro-bend causing light to leak out of the optical fibre. Since the power density of a selected channel in the selection region is substantially higher than the power density of other channels, the loss predominantly affects the selected channel. Another feasible approach to achieve tuneable loss is to utilise evanescent coupling of light from the selection region. By controlling the distance between a probe and the waveguiding structure, the power coupled out from the waveguiding structure can be controlled. Yet another method of inducing a loss is to utilise controllable liquid crystals, in which the transmittance can be arbitrarily varied.

Furthermore, no feedback to the sender (the transmitter) is needed although pre-equalising is certainly possible within the scope of the present invention.

It is important to understand that the term channel balancing does not imply that the power level of all channels should be made equal. Conversely, the power levels of the channels could be adjusted to any desired value. Thus, the present invention provides channel selective power control, thereby allowing control of the

power distribution between channels in a WDM or DWDM optical signal.

It is to be understood that all the embodiments of the present invention are inherently serial, in that any
 5 number of resonators (or selection regions) can be arranged in cascade. Thus, there is no limitation on the number of channels that can be balanced (i.e. individually attenuated).

10 Brief description of the drawings

In the following, a number of preferred embodiments of the present invention will be described in detail. The description below is more easily understood when read in conjunction with the drawings, in which

15 figure 1 schematically shows an arrangement according to the present invention comprising external resonators;

figure 2 schematically shows an arrangement according to the present invention having a super dynamic
 20 capability;

figure 3 schematically shows a magnified picture of an arrangement according to the present invention;

figure 4 schematically shows an arrangement according to the present invention comprising external
 25 resonators in which controllable absorbers are provided;

figure 5 schematically shows an arrangement according to the present invention comprising controllable absorbers and having a super dynamic capability;

30 figure 6 schematically shows how a super dynamic filtering capability is achieved;

figure 7 schematically shows an input signal, a filter function and a filtered output signal;

figure 8 schematically shows, in block form, a set-
 35 up for channel balancing of an optical signal propagating in a fibre;

figure 9 schematically shows, in block form, a set-

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up for channel balancing, including a pre-amplifier and a power-amplifier for amplifying the optical signal;

figure 10 schematically shows an arrangement according to the present invention comprising two fibres provided within external resonators;

figure 11 schematically shows an arrangement according to the present invention comprising two fibres with internal resonators; and

figure 12 schematically shows two embodiments of an arrangement according to the present invention comprising a single fibre with internal resonators.

Throughout the drawings, like parts are designated by like references.

Detailed description of preferred embodiments

A first preferred embodiment of an arrangement according to the present invention is schematically shown in figure 1. The arrangement shown is to be regarded as the best mode of carrying out the invention, based on current knowledge.

Figure 1 shows a channel balancing arrangement 10 having an input fibre 1 that is connected to an optical circulator 2. The circulator 2 is arranged to direct light coming from the input fibre 1 into an intermediate fibre 3, and to direct light coming from the intermediate fibre 3 into an output fibre 4. Channel balancing according to the present invention is accomplished in the intermediate fibre 3. The fibres 1, 3 and 4 are all capable of carrying a wavelength division multiplexed optical signal.

The intermediate fibre 3 comprises a chirped Bragg grating 5 (shown in the figures as vertical bars with increasing separation), which reflects all light within a predefined wavelength range back towards the circulator 2. The chirped grating 5 acts as a distributed back-reflector for light entering the intermediate fibre 3; different wavelengths are back-reflected at

different positions of the chirped grating 5. Hence, if the intermediate fibre 3 is inactive, the optical signal will continue down the communications link on the output fibre 4 much as if the intermediate fibre 3 and the circulator 2 was not there.

However, at the intermediate fibre 3, there is arranged a plurality of external resonators 6, each of which is defined by a first 7 and a second 8 mirror arranged outside and on opposite sides of the fibre 3. Furthermore, each external resonator 6 is coupled to the intermediate fibre 3 by a respective deflector 9. The deflectors 9 are preferably comprised of tilted, i.e. blazed, Bragg gratings that are superimposed on the chirped Bragg grating 5 in the intermediate fibre 3, and arranged to deflect light from the fibre 3 and into the respective external resonator 6, and to deflect light from each respective external resonator 6 into the fibre 3.

The deflecting power of the deflectors 9 can be very low, only a very small fraction of light in the fibre 3 being deflected into each external resonator 6. However, the chirped grating in the fibre governs, in the region where each wavelength is reflected, the accumulation of power for that wavelength. Thus, the deflected power of any one wavelength can be enhanced by providing the deflector in the region where said wavelength is reflected by the chirped Bragg grating. At equilibrium, the coupling of light to and from the resonator will be equal. The power of the resonant wavelength will be significantly increased inside the resonator, and will be coupled back into the intermediate fibre by the associated deflector. Note that since light is reflected back and forth in the resonators, the deflector (i.e. the tilted Bragg grating) will couple light back into the fibre in both propagation directions. By making the refractive index modulation of the chirped grating 5 sufficiently large, a second resonance can be obtained in

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the chirped grating 5, which resonance further increases the coupling of power of the resonant wavelength. The mechanism behind the resonantly enhanced coupling in connection with a chirped Bragg grating is

- 5 comprehensively described in the aforementioned co-pending application "Optical Coupling" (US App. 09/608 218).

The part of the optical signal not entering any external cavity 6 will, as indicated above, be back-
10 reflected by the chirped grating 5. At each deflector 9, the back-reflected light of one wavelength will interfere with light coupled out of the respective external resonator 6. By adjusting the external resonator, preferably by a parallel displacement of the two mirrors
15 7 and 8 with respect to the fibre 3, destructive interference can be achieved such that no light of the resonant wavelength can return to the optical circulator 2. Alternatively, destructive interference can be achieved by altering the optical path length of the
20 external resonator by changing the refractive index in at least some portion thereof. Consequently, the corresponding wavelength channel is eliminated from the multiplexed optical signal. When light of one channel is prohibited to return to the circulator 2 in this way,
25 light energy is instead forced to leave the system elsewhere, for example through the chirped grating 5 or through either of the resonator mirrors 7, 8.

It is to be understood that different levels of destructive interference can be obtained by adjusting the
30 external resonators. This means that each channel can be fully blocked or fully passed, as well as partly blocked to any desired degree.

Hence, the external resonators provide selection regions where corresponding channels are singled-out from
35 the multiplexed optical signal. Each of the external resonators 6 is individually adjustable so that, by

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cascading such resonators, attenuation can be effected simultaneously on any number of channels.

The arrangement shown in figure 1 is provided in an optical communications link, in which a WDM signal or a DWDM signal is propagated. The optical signal enters the optical circulator 2 from the input fibre 1; and is directed into the intermediate fibre 3 where the channel balancing is performed. From the intermediate fibre 3, light is directed into the output fibre 4 by the optical circulator 2 for further transmission down the communications link. Thus, the arrangement 10 is designed to be connected anywhere in an existing optical network.

An external resonator can also be tuned to be resonant to any wavelength within the tuning range by changing the separation between the first 7 and the second 8 mirror, or by tilting the external cavity 6 in its entirety with respect to the fibre 3. In this way, more than one resonator can be made resonant to almost the same wavelength. Consequently, one channel within the multiplexed optical signal can be filtered (attenuated) by more than one selection region. This feature gives the arrangement according to the invention great versatility and provides a "super dynamic" capability, i.e. the capability of shaping the filter function. This super dynamic capability will be further described with reference to figure 2.

The variable attenuation by destructive interference will now be described in greater detail with reference to figure 3. Figure 3 is a schematic magnified picture of one external resonator 6 and its associated deflector 9. Also shown in the figure is the back-reflecting grating 5, now shown as a plane mirror in the waveguiding structure 3. The blazed grating, constituting the deflector 9, is shown as a single domain between the resonator mirrors. The above simplifications are for the purposes of graphical clarity only.

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Now, in the lower part of the external resonator 6a, two beams are superimposed; namely light from the back-reflector 37 and light from the upper resonator mirror 35. On the other hand, two beams are also superimposed in the waveguiding structure to the left of the deflector. For clarity only, the beams are shown with a small offset. By a parallel displacement of the external resonator 6 with respect to the waveguiding structure 3, or by changing the refractive index in at least some portion of the external resonator, destructive interference between the two superimposed beams can be obtained either in the lower part of the external resonator (beams 35 and 37), or in the waveguiding structure to the left of the deflector (beams 34 and 36). Consequently, if destructive interference is obtained in the waveguiding structure to the left of the deflector, all light is forced into the external resonator 6. The

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channel at issue is thus blocked from returning to the circulator 2 (not shown in figure 3). On the other hand, if destructive interference is obtained in the lower part of the external resonator 6a, light is actually prevented from entering the external resonator 6 at all, and hence all light is transmitted back towards the circulator 2. The channel at issue is thus unaffected and transmitted back to the circulator 2 in its entirety.

Figure 2 shows schematically an arrangement according to the present invention having a super dynamic capability. Each of the external resonators 6, as compared to the arrangement shown in figure 1, is divided into six separate external sub-resonators. It is to be understood that any number of sub-resonators is conceivable, the shown embodiment of six sub-resonators being an example only. In this embodiment, a wavelength division multiplexed optical signal coming into the optical circulator 2 from the input fibre 1 is directed into the intermediate fibre 3. In the intermediate fibre 3, separate channels of the optical signal are attenuated individually, i.e. channel balancing is performed. When it comes back to the optical circulator 2 from the intermediate fibre 3, the optical signal is directed into the output fibre 4 for further transmission down the optical communications link.

In the intermediate fibre 3, there is provided a chirped Bragg grating 5, reflecting essentially all light within a predefined wavelength range. Thus, if the optical signal is not manipulated with in the intermediate fibre 3, the signal will return to the optical circulator 2 and be directed into the output fibre 4. At the intermediate fibre 3, there is arranged a plurality of external resonators 6, each of which comprises a plurality of sub-resonators. In fact, a sub-resonator is not different from any other external resonator, the expression sub-resonator being used only to point out that a plurality of resonators is coupled

to, or associated with, a common channel within the optical signal. The external resonators 6 are coupled to the intermediate fibre 3 by deflectors superimposed on the chirped Bragg grating in the intermediate fibre. The
5 deflectors are arranged to deflect light from the intermediate fibre 3 into the respective external resonator 6, and to deflect light from each external resonator 6 into the intermediate fibre 3.

The super dynamic capability of the arrangement
10 shown in figure 2 is provided by the sub-resonators in each external resonator. As mentioned above, each external resonator is divided into a plurality of individual sub-resonators, each having its own phase and its own resonant wavelength. Each sub-resonator is
15 defined by a pair of sub-mirrors, said sub-mirrors being individually controllable in order to allow tuning of the phase and the resonant wavelength of each sub-resonator individually. It is important to understand that when a plurality of external resonators is coupled to a common
20 channel within the optical signal, these external resonators are named sub-resonators (to that particular channel). Consequently, the effects of all sub-resonators are superimposed on each other when the resonant channels are deflected back into the intermediate fibre.

25 Although it could be possible to achieve a super dynamic capability with distributed resonators, each having its own deflector, it is preferred that the super dynamic capability for each channel is provided by a plurality of sub-resonators arranged adjacent to each
30 other, and coupled to a common channel within the WDM or DWDM optical signal. With such an arrangement, the chirped grating that enhances the coupling between the external resonators and the intermediate fibre can be utilised effectively.

35 As illustrated in figure 6, each sub-resonator is adjusted to a different resonant wavelength and adjusted to provide a desired attenuation, thereby constituting,

in fact, six different filters for the one and same channel. The superposition of these six filters provides the super dynamic capability of the arrangement shown in figure 2. By tuning the sub-resonators individually, the
5 resulting filter function for a channel can be flattened, broadened or modified. The filtering is therefore said to be super dynamic, and the arrangement exhibits a super dynamic capability.

Referring now to figure 4, an embodiment related to
10 that shown in figure 1 comprises controllable absorbers 12 or similar means inside the external resonators 6. In this case, the resonators need not be tuneable themselves as long as they are adjusted to the proper wavelength. Rather, controllable attenuation is provided by said
15 absorbers 12. This embodiment is somewhat simpler than the foregoing, in that it lacks some of the features of the arrangement above. However, in many cases this less elaborated arrangement may be preferred by virtue of its simplicity.

20 The external resonators of the embodiment shown in figure 4 are typically arranged to provide constructive interference between back-reflected light from the chirped grating and light coupled out from the resonators. Attenuation is achieved by changing the
25 amplitude of the light from the resonators. In an exemplary situation, half of the channel power could be deflected into the external resonator and half of the power could be back-reflected by the chirped grating. If no absorption takes place in the external resonator, the
30 channel is not attenuated. On the other hand, if all light in the external resonator is absorbed, the channel power is halved. Thus, the embodiment of figure 4 could not, in the case indicated above, be used to eliminate a channel from the wavelength division multiplexed optical
35 signal, but only to reduce the signal strength by half. However, in most practical applications, this is sufficient indeed.

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division multiplexed optical signal is propagated in an optical fibre. The different channels have different signal powers, as indicated in the uppermost diagram of figure 7. The optical signal is launched into an
5 arrangement for channel balancing according to the present invention. In the illustrated case, all channels are selected for attenuation and the desired result is that all channels should have the same power level (signal strength). For each of the channels, a resonance
10 is established that provides a respective selection region. Each selection region is then adjusted so that proper attenuation D is applied to each channel. In other words, transmission windows are provided for each channel, as indicated in the centre diagram of figure 7.
15 When the optical signal has passed through the transmission window (actually, when each channel has been attenuated by a desired amount), it is coupled into the transmission fibre carrying the signal (corresponding to the output fibre of the arrangement 10. Consequently, the
20 optical signal has been subject to channel balancing, in which the strength of all channels has been equalised, as indicated in the lowermost diagram of figure 7.

By using other levels of attenuation for each channel, it is straightforward to achieve any power
25 profile of the balanced signal.

Figure 8 illustrates how channel balancing according to the present invention is implemented at an optical communications link. An attenuator arrangement 10 according to any one of the embodiments of the present
30 invention is connected to an optical fibre 40 capable of carrying a wavelength division multiplexed optical signal. A controller 41 is operatively connected to the attenuating arrangement 10 in order to control the channel balancing. Downstream and/or upstream in the
35 fibre 40 from the attenuating arrangement 10 there is provided a spectrum analyser 42. The spectrum analyser 42 is arranged to analyse the power spectrum of the optical

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5 resonators are omitted. In this case, instead, internal resonators are utilised, which are constituted by a chirped Bragg grating 5 of strong index modulation in each fibre. Attenuation of an individual channel is easily achieved by introducing an absorber 12 between the two fibres. One channel is deflected from one fibre to the other by deflectors 9 superimposed on the chirped Bragg grating in the two fibres. Although the resolution of a filter according to the embodiment shown may not be as good as for the embodiment of figure 10, it may still be preferred by virtue of its simplicity.

35 Note that the power density of the resonant wavelength is increased in the selection region. This

allows of a small enough loss to be used not to affect other wavelengths (other channels).

Alternatively, the loss can be introduced by moving a probe close to the waveguiding structure, thereby
5 causing evanescent coupling of light out from the same, as shown in the upper picture of figure 12. The amount of light coupled out depends on the separation of the probe from the waveguiding structure. Preferably, if evanescent coupling is used for attenuating the optical signal, the
10 cladding of fibre is partly removed in order to allow evanescent interaction with light in the core of the fibre.

It is to be understood that each resonator or resonant portion in the attenuating arrangement is, in
15 fact, a dynamic optical coupler. The dynamic optical coupler can be utilised to remove a controlled amount of power from the resonant wavelength channel. For example, the dynamic optical coupler can be used as an add/drop device for adding and/or dropping a selected channel to
20 or from a wavelength division multiplexed optical signal propagating in an optical fibre.

Optical fibres that are commonly used for communication purposes are usually not polarisation maintaining. Therefore, it is preferred, and in some
25 cases essential, that the channel specific power control according to the present invention is performed on two orthogonal polarisation directions. It is preferred, for example, that the WDM optical signal is separated into two orthogonal polarisation components and sent into a
30 respective polarisation maintaining fibre, in which channel selective power control (or channel balancing) according to the present invention is performed on both components separately and in concert. Subsequently, the two components are recombined into the transport fibre
35 (which is typically not polarisation maintaining) after having been subject to said power control.

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